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Flexible Spectrum Management in a Smart City Within Licensed Shared Access Framework

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ABSTRACT The new generation of communication technologies, named 5G, brings along a variety of emerging applications and services from both human and machine perspectives. The growing demand for bandwidth in 5G may therefore lead to massive deficiency in wireless spectrum availability despite its underutilization in urban areas. The Smart City paradigm assumes a multitude of communicating machines at high density, which requires improved spectrum management flexibility. The novel licensed shared access (LSA) framework that has attracted recent industrial and academic attention may become a feasible solution to leverage such underutilized spectrum more efficiently. This paper analyzes the effects of applying LSA in the Smart City context by proposing an appropriate mathematical model. Particularly, we focus on the vehicle-to-everything 5G use case where connected devices attempt to distribute their sensed data including occasional video information. The proposed analytical framework allows to capture the probabilities of rare events during such operation by providing with a high level of precision in the resulting performance estimates.

INDEX TERMS Licensed Shared Access, Smart City, Admission control, Quality of service, 5G mobile communications.

I. INTRODUCTION AND BACKGROUND

The advent of next generation of wireless networks (5G) gives rise to new challenges, particularly, in spectrum capacity. It has been estimated that spectrum limit will be reached by 2025 [1], [2]; hence, new strategies of efficient wireless spectrum utilization are essential [3]. At the same time, the number of interconnected and autonomously operated low-cost devices is growing tremendously [4] as the vision of Smart City is taking shape [5]. Communication is envisioned to become less human oriented and more leans toward Machine-to-Machine (M2M) communication [6].

An example of M2M communication paradigm in 5G networks is an automated Smart City, where a high number of interconnected and remotely controlled machines form an extensive urban-scale machine-type communication (MTC) cluster within high-density environment [7], [8]. Despite the connectivity enablers, a large number of applications are envisioned in the Smart City context, including e.g., wireless sensor networks [9], industrial automation [10], smart grid [11], public safety [12], smart metering [13], smart parking [14], e-healthcare [15], smart house and office

automation [16], and green energy [17], among others.

Since most of these applications are machine-oriented [18], the interconnected sensors may become an integral part of the environment, especially in the Vehicle-to-Everything (V2X) scenario [19]. The surge in the number of communicating machines is expected to influence spectrum utilization even more, as present-day wireless networks were developed to be primarily utilized by humans [20]. The management techniques were therefore designed to satisfy the need for bandwidth with predictable request and access policies [21], while machines are expected to communicate in a more unpredictable manner.

One of the enablers for dynamic wireless spectrum management is the emerging Licensed Shared Access (LSA) framework, which permits more flexible spectrum control for highly demanding applications of tomorrow [22], [23]. At the same time, LSA allows for improved radio resource utilization by relocating inactive or unused frequency bands. Considered from the communication point of view, LSA is a highly promising concept due to the possibility of providing predictable shared-spectrum operation with certain

Quality-of-Service (QoS) guarantees. For example, the vertical sharing structure of LSA permits multiple spectrum users in the same area to operate according to the priority tiers, see in Fig. 1.

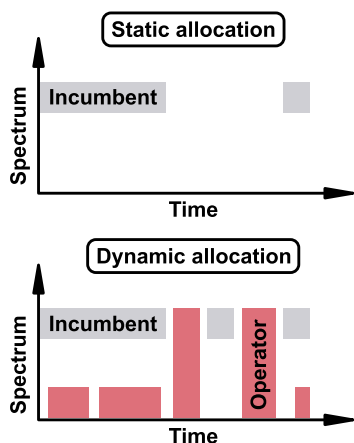


FIGURE 1. Conceptual operation of dynamic LSA framework.

More precisely, LSA allows for controlled spectrum sharing between two parties: (i) current owner of the spectrum, named the incumbent, and (ii) a temporary user, named the LSA licensee. Both parties obtain access to the same frequency band in a mutually agreed manner [24]. The envisaged LSA framework enables flexible infrastructure operation [25]. The spectrum is provided depending on a set of constraints i.e., in terms of time, frequency, and bandwidth. After the spectrum sharing request is confirmed, it is further forwarded to the corresponding spectrum owner and next translated into the Radio Access Network (RAN) instructions i.e., transmit power, interference- and frequency-related configuration, LSA policy, etc.

If the commands are successfully received and accepted, RAN executes the required actions according to the predefined instructions. Recently, a number of policies for efficient interference coordination between an incumbent and the LSA licensees were described in literature. The authors in [26] consider different approaches: (i) ignore policy and (ii) limit power policy (used for aeronautical telemetry). This work was further extended with respect to shutdown policy in [27].

For the V2X scenario, LSA may act as a powerful enabler leveraging the available secondary spectrum in the areas with low population densities as well as allowing for spectrum sub-utilization in dense areas during off-peak hours i.e., when the conventional users do not require most of the spectrum. A large number of characteristic LSA scenarios are being considered from the business perspective: Programme making and special events (PMSE) [3]; Public Safety [28]; Smart City [29], [30], and many others [31].

In what follows, we study a typical LSA use case, where the spectrum license owner in an urban area requires its frequency resources only occasionally, in small and local-

ized portions. Based on the assumption that cellular network availability in the city is high, the incumbent (the network operator) has an opportunity to request underutilized spectrum for the rest of the time.

The remainder of this text is organized as follows. In Section II, a detailed summary of our proposed LSA-aware system model suitable for Smart City operation is discussed. Next, in Section III the corresponding analytical model based on a continuous Markov Chain formulation is provided. Further, we propose a recursive algorithm that employs the needed calculations in Section IV. Section V provides selected numerical results supporting the LSA utilization possibilities. The last section concludes this work.

II. BACKGROUND AND SYSTEM MODEL

In this paper, we focus on the scenario that considers a cooperative intelligent transportation system (ITS). The main objective of the ITS is to reach enhanced safety on the roads by using V2X communication in a Smart City [32] by video and telemetry exchange between the connected entities. The data are sent from each node involved into the system operation and further periodically delivered to the cloud control framework for further storage and analysis. At the same time, the spectrum owner may temporarily allocate it to V2X nodes except for the infrequent cases of its own data collecting periods.

Since the topic of LSA is only attracting the attention of the community recently, the number of works on the corresponding simulation-based evaluations is rather large while the analytical side remains underrepresented. The authors in [33] consider various network-management scenarios. Particular attention is paid to allocating bandwidth for M2M devices, which is expected to be one of the key drivers for shared resource access. The main idea of that work is that, unlike in the currently allocated spectrum, most of new frequencies (about 80%) are expected to remain in common use i.e., either under the LSA rules or with opportunistic access spectrum (OSA) model. This research proposes conceptual reasoning behind the types of scenarios, while the actual analytical models are not provided.

The authors of [34] elaborate on the LSA system operation with two base stations (BSs), primary and secondary. The users of the secondary BS can be served only when transmission does not degrade the QoS at the primary BS below a certain level; otherwise, the secondary BS is kept in idle mode. To achieve this goal, both BSs are assumed to be perfectly synchronized. The analytical contribution proposed in that work enables joint scheduling for two BSs. Further, the authors of [35], [36] propose a mechanism for distributing the LSA spectrum between several LSA licensees using a joint auction with mixed graph mechanism. This scheme allows for unhindered access to common spectrum by different (unknown to each other) commercial operators, whose BSs are coordinated with a dedicated management entity.

An optimized belief-based decision-making framework is proposed in [37]. That work develops a solution,

which exploits Cognitive Radio technology to mitigate the spectrum scarcity problem by enabling Dynamic Spectrum Access (DSA). The provided model is evaluated with both simulations and prototyping. The authors in [38] focus on capturing spatial user locations, which become a crucial factor with respect to the system performance. This approach combines queuing theory and stochastic geometry, while the actual analysis is conducted for the 3GPP LTE cellular system. However, the LSA framework is not taken into consideration in that work.

In contrast to the models available in the literature, our proposed framework utilizes Markov chain based analysis, since this approach is powerful, relatively simple to use, could be understood by a broad audience, and at the same time remains rather precise. However, other alternative techniques could also be applied in this context [39]. We have already completed a preliminary evaluation of the relevant QoS and QoE aspects by utilizing methods based on a similar approach in [38]. Indeed, the shortage of available spectrum has become a major barrier in developing today’s wireless systems. This leads to insufficient radio resources and may compromise the required levels of QoS and QoE for the users.

In our current model, we analyze one urban wireless cell of radius R with the BS located in its geometrical center, and k uniformly distributed vehicles located within the area of interest, see Fig. 2. When the considered devices are active, they operate in the full-buffer mode i.e., if the device enters the active mode, it attempts a transmission immediately. The idle-to-active rate is λ , while the user data transmission follows an exponential distribution with the parameter μ .

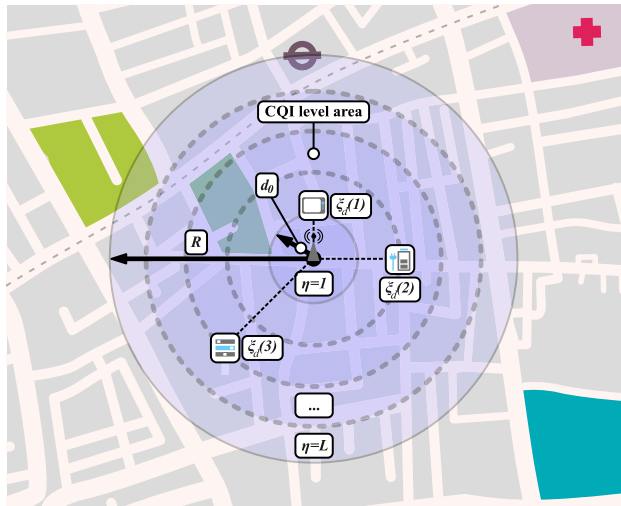


FIGURE 2. Considered system topology.

Each node has its unique Channel Quality Indicator (CQI) value c in the range $[1..15]$ (higher value of c corresponds to better possible throughput). Further, we assume that all of the users with the same CQI are grouped into the corresponding coalition with similar maximum distance to the BS and certain throughput. The maximum distance between the node

and the BS is defined as $\xi_d(\eta) = RL^{-1}\eta$, where $\eta = 16 - c$. Due to the uniform distribution of devices across the area of interest, the density function is $f_{\xi_d(\eta)}(d) = \frac{2d}{R^2}$, $0 \leq d \leq R$. Then, the CDF $F_\eta(l)$ of the random variable $\eta = 1, \dots, L = 15$, is: (i) $F_\eta(l) = 0$ if $l < 0$; (ii) $F_\eta(l) = (\frac{l}{L})^2$ if $0 < l < L$; or (iii) $F_\eta(l) = 1$ if $l > L$.

In this paper, we focus on the LSA frequency bands utilized by e.g., law enforcement units for communication with vehicles. The operators that own the frequencies are seldom renting them to the command center via the BS in order to enhance the network performance. Further in this work, we assume that the average time of the vehicle’s travel over the connectivity area is β^{-1} , and α^{-1} is the average idle spectrum duration. To increase the LSA spectrum usage efficiency, we utilize the Full Power (FP) policy i.e., the bandwidth is constant ω and the data transmissions are executed at the maximum transmit power p_1^{max} in case the spectrum owner does not utilize it. Otherwise, the transmit power is limited to $p_0^{max}, p_0^{max} < p_1^{max}$ for the communicating devices.

Clearly, the transmit power variations cause changes in the data throughput as $r(\xi_d(\eta), p_s^{max})$, $s = 0, 1$, which depends on the distance between the BS and the device. According to the Shannon’s formula, the corresponding dependency is captured as

$$r(\xi_d(\eta), p_s^{max}) = \omega \ln \left(1 + \frac{G p_s^{max}}{\left(\frac{R}{L} \eta\right)^\kappa N_0} \right), \quad (1)$$

where $s = 0, 1$, N_0 is the noise power, G is the propagation constant, and κ is the propagation exponent.

One of the system requirements is the guaranteed lower limit r_0 on the delivered throughput for each device. In case r_0 cannot be provided, the request is being blocked. If the device is in “infinitely” close proximity to the BS, its throughput theoretically tends to infinity. To limit this effect, we introduce the minimum distance between the BS and the device $\xi_d(1)$ as d_0 , and constrain the maximum throughput as $r_s^{max} = r(d_0, p_s^{max})$, $s = 0, 1$. Therefore, the maximum throughput can be represented as $r(\xi_d(\eta), p_s^{max}) = r_s^{max}$ with $\eta = 1$ or by applying (1) with $\eta = 2, \dots, L$. The core system modeling parameters used in this work are summarized in Table 1.

III. ANALYTICAL METHODOLOGY

To analyze the scenario described above, in this section we introduce a Markovian process based analytical model. The behavior of the system states can be described by a continuous Markov chain (CMC) $\{\xi(t), \eta_1(t), \dots, \eta_{\xi(t)}(t), \zeta(t), t \geq 0\}$, where $\xi(t)$ is the number of active devices, $\eta_i(t)$, $i = 1, \dots, \xi(t)$ is the value of the random variable η that defines the CQI level reported by the i^{th} device, and $\zeta(t)$ is the state of the multi-tenant band at $t \geq 0$. Therefore, the system operation could be defined as (k, l_1, \dots, l_k, s) ; $l_i = 1, \dots, L$; $k = 0, 1, \dots$; and $s = 0, 1$.

Before continuing with the general scenario, we consider a particular case with unlimited transmit power. Then, the system states are described as in (2), as shown at the bottom of

TABLE 1. Main modeling parameters.

Notation	Parameter description	Units
R	Cell radius	m
ω	Bandwidth of uplink channel	MHz
L	Number of CQI levels	-
$c = 16 - \eta$	Value of reported CQI level (random variable)	-
$q_l = \frac{2L-2l-1}{L^2}$	Probability that the reported CQI level is equal to l	-
α^{-1}	Average time when multi-tenant band is available	s
β^{-1}	Average time when multi-tenant band is unavailable	s
s	State of the multi-tenant band, $s = 1$ if the band is available and $s = 0$ if the band is unavailable	-
k	Number of active devices	-
K_0	Maximum number of devices when multi-tenant band is unavailable	-
K_1	Maximum number of devices when multi-tenant band is available	-
p_0^{max}	Threshold value of maximum uplink power of devices when multi-tenant band is unavailable	W
p_1^{max}	Threshold value of maximum uplink power of devices when multi-tenant band is available	W
$\xi_{d(\eta)}$	Maximum distance to the BS (random variable)	m
d_0	Minimum distance to the BS	m
r_0	Guaranteed bit rate	bps
r_0^{max}	Maximum bit rate when multi-tenant band is unavailable	bps
r_1^{max}	Maximum bit rate when multi-tenant band is available	bps
$r(\xi_{d(\eta)}, p_s^{max}), s = 0, 1$	Achievable bit rate	bps
λ	Arrival rate of sessions to transmit data	1/s
μ^{-1}	Average service time of one device	s
$\rho = \lambda/\mu$	Offered load	-

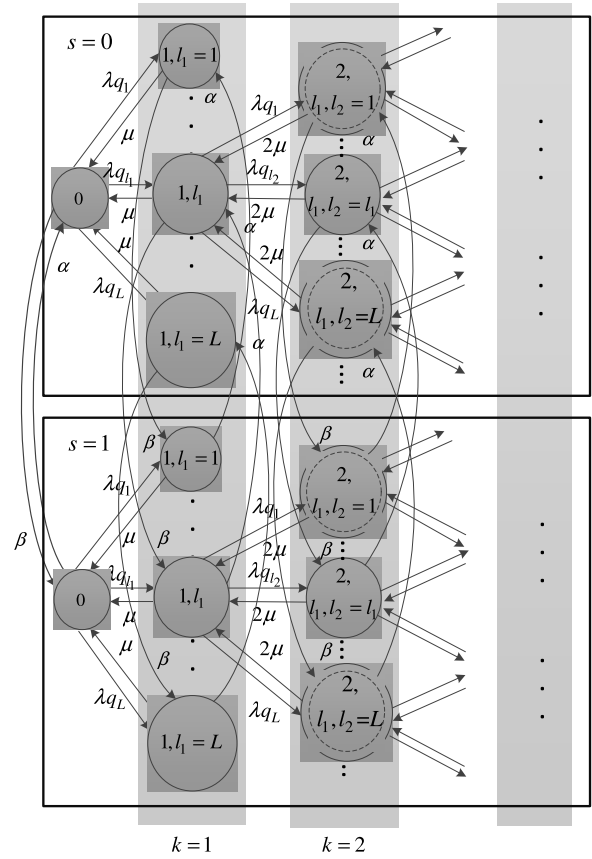


FIGURE 3. Considered transition state machine.

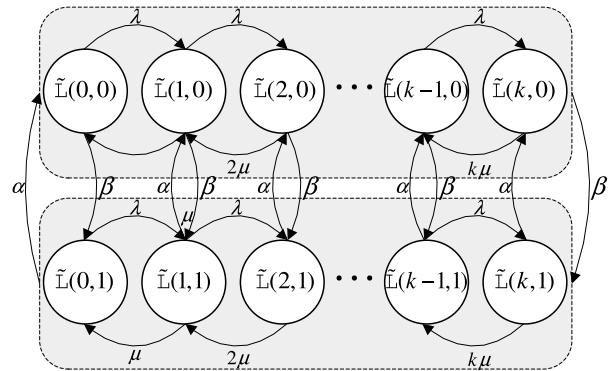


FIGURE 4. Aggregated transition state machine.

the next page.

Assume that the random variable η would be equal to l with the probability $q_l, l \in \{1, \dots, L\}$. Consider our assumption regarding the uniform distribution of users across the network coverage zone, $q_l = \frac{2L-2l-1}{L^2}, l = 1, \dots, L$. Next, if there are k users with some CQI ($c = 16 - l_i, i = 1, \dots, k$) value assigned to each of them and the shared bandwidth is s , then the transition state machine can be considered as illustrated in Fig. 3.

In order to simplify the calculation process, we aggregate the states based on the user number k . Therefore, $\tilde{L} = \bigcup_{k=0}^{\infty} (\tilde{L}(k, 1) \cup \tilde{L}(k, 0)), \tilde{L}(K) = \{(k, l_1, l_2, \dots, l_k, s) \in L\}$, and the updated state machine is given in Fig. 4.

Realistically, the transmit power is not infinite and thus the maximum number of served devices is limited. Therefore, the system description should be updated as $\{\xi(t), \eta_1(t), \dots, \eta_{\xi(t)}(t), \zeta(t), t \geq 0\}$ in $L \subset \tilde{L}$. We introduce

the access function according to the Full Power policy as

$$g_{\xi_{d(\eta)}}(k, l_1, l_2, \dots, l_k, s) = \begin{cases} 1, & \text{if } \sum_{i=1}^k \frac{r_0}{r(\xi_{d(\eta)}, p_s^{max})} \leq 1; \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Next, we split the states L by the number of active devices k as $L = \bigcup_{k=0}^{\infty} (L(k, 1) \cup L(k, 0)), L(k, s) = \{(k, l_1, \dots, l_k, s) \in L\}$. Considering (3), $L(k, s)$ is further

represented as

$$L(k, s) = \left\{ 0 \leq d_1 \leq R, \dots, 0 \leq d_k \leq R : \right. \\ \left. \times \sum_{i=1}^k \frac{r_0}{\omega \ln \left(1 + \frac{Gp_s^{max}}{d_i^\kappa N_0} \right)} \leq 1 \right\}. \quad (4)$$

Let us define $P_s(k)$, $s = 0, 1$ as a conditional probability of $k + 1^{th}$ to be served with $l_{k+1} \in \{1, \dots, L\}$ when there are already k served devices with the same CQI as $P_s\{(k + 1, s) \in L(k + 1, s) | (k, s) \in L(k, s)\}$. In case the number of served devices is zero, the probability of a new device to be served is

$$P_s(0) = F_{\xi_{d(\eta)}} \left(\min \left\{ R, \left(Gp_s^{max} / (e^{r_0/\omega} - 1) N_0 \right)^{1/\kappa} \right\} \right). \quad (5)$$

The remaining conditional probabilities $P_s(k)$, $k > 0$ are further estimated based on (3) as

$$P_s(k) = \frac{P \left\{ \sum_{i=1}^{k+1} \frac{1}{r(l_i, p_s^{max})} \leq \frac{1}{r_0}, \sum_{i=1}^k \frac{1}{r(l_i, p_s^{max})} \leq \frac{1}{r_0} \right\}}{P \left\{ \sum_{i=1}^k \frac{1}{r(l_i, p_s^{max})} \leq \frac{1}{r_0} \right\}}. \quad (6)$$

According to the central limit theorem, the sum of the random variables $1/r(l_i, p_s^{max})$ may be approximated as

$$\sum_{i=1}^k \frac{1}{r(l_i, p_s^{max})} \approx N(k\theta, k\sigma^2), \quad (7)$$

where θ and σ are the expected value and the variance of the independent and identically distributed random variables $1/r(l_i, p_s^{max})$, correspondingly.

Due to the continuity feature of the standard normal distribution function, the convergence to this distribution is equivalent to the point-wise convergence of the distribution functions to the distribution function of the standard normal distribution. Hence, $Z_k = S_k - \theta k / \sigma \sqrt{k}$, where $S_k = \sum_{i=1}^k 1/r(l_i, p_s^{max}) \leq 1/r_0$. Next, we obtain $F_{Z_k}(x) \rightarrow \Phi(x)$, $\forall x \in R$, where $\Phi(x)$ is the standard normal distribution function. Therefore,

$$P \left(\sum_{i=1}^k \frac{1}{r(l_i, p_s^{max})} \leq \frac{1}{r_0} \right) = \Phi \left(\frac{1 - \theta k r_0}{r_0 \sigma \sqrt{k}} \right), \quad (8)$$

where $\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-\frac{t^2}{2}} dt$.

To further simplify the evaluation, we introduce

$$m_k = kr_0 E \left[1/r(l_i, p_s^{max}) \right], \\ \tau_k^2 = kr_0 \left(E \left[\left(1/r(l_i, p_s^{max}) \right)^2 \right] - \left(E \left[1/r(l_i, p_s^{max}) \right] \right)^2 \right).$$

Then, $P_s(k)$, $k > 0$ could be obtained with

$$P_s(k) = \Phi \left(\frac{1 - m_{k+1}}{\tau_{k+1}} \right) / \Phi \left(\frac{1 - m_k}{\tau_k} \right). \quad (9)$$

Next, the expected value of the random variable $1/r(l_i, p_s^{max})$ is

$$E \left[1/r(l_i, p_s^{max}) \right] = \left(1/r_s^{max} \right) F_{\xi_{d(\eta)}}(d_0) \\ + \int_{d_0}^R \frac{1}{\omega \ln \left(1 + Gp_s^{max} / x^\kappa N_0 \right)} f_{\xi_{d(\eta)}}(x) dx, \quad (10)$$

and for $\left(1/r(l_i, p_s^{max}) \right)^2$ is

$$E \left[\left(1/r(l_i, p_s^{max}) \right)^2 \right] = \left(1/r_s^{max} \right)^2 F_{\xi_{d(\eta)}}(d_0) \\ + \int_{d_0}^R \frac{1}{\omega^2 \ln^2 \left(1 + Gp_s^{max} / x^\kappa N_0 \right)} f_{\xi_{d(\eta)}}(x) dx. \quad (11)$$

The maximum number of users is $K_s = r(d_0, p_s^{max})/r_0$, with $s = 1$ in case where the multi-tenant band is available or $s = 0$ otherwise. Then, L could be represented as

$$L = \{(k, s) \in \{0, 1, \dots, K_s\} \times \{0, 1\}\}. \quad (12)$$

Further, the rules of the serving procedure for the active nodes for the LSA scenario are listed as follows:

- 1) The device will be served on the multi-tenant band with the maximum downlink power p_1^{max} , which is possible if the multi-tenant band is available i.e., $s = 1$ and the number of devices serviced on the multi-tenant band is less than K_1 .
- 2) The device will be served on the multi-tenant band with the maximum downlink power $p_0^{max} < p_1^{max}$, which is possible if the multi-tenant band is unavailable i.e., $s = 0$ and the number of devices serviced on the multi-tenant band is less than K_0 .
- 3) Otherwise, the device's request will be blocked without any after-effect for the corresponding Poisson process.

$$\tilde{L} = \left\{ (0, 1), (1, 1, 1), \dots, (1, L, 1), (0, 0), (1, 1, 0), \dots, (1, L, 0), (2, 1, 1, 0), \dots, (2, L, L, 0), (2, 1, 1, 1), \dots, \right. \\ \left. \times (2, L, L, 1), \dots, \left(k, \underbrace{1, \dots, 1}_k, 1 \right), \dots, \left(k, \underbrace{L, \dots, L}_k, 1 \right), \dots, \left(k, \underbrace{1, \dots, 1}_k, 0 \right), \dots, \left(k, \underbrace{L, \dots, L}_k, 0 \right) \right\} \\ = \left\{ (0, s), (k, l_1, l_2, \dots, l_k, s), k = 1, 2, \dots, l_i \in \{1, \dots, L\}, i = 1, \dots, k, s = 0, 1 \right\}. \quad (2)$$

Importantly, when the multi-tenant LSA band is deactivated, the maximum link power also changes from P_1^{max} to P_0^{max} . Therefore, the serving rate also decreases down to $k - K_0$, $k > K_0$. In the opposite case, the transmit power increases, and the steady state diagram is shown in Fig. 5.

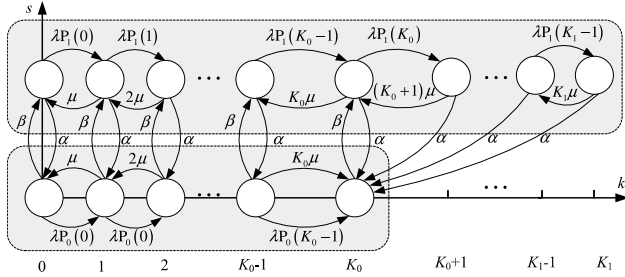


FIGURE 5. Markov chain for LSA system operation.

The corresponding Markov process representing the system states is described with the system of equilibrium equations as

$$\begin{cases} p(0, 0)(\lambda P_0(0) + \beta) = p(1, 0)\mu + p(0, 1)\alpha; \\ p(0, 1)(\lambda P_1(0) + \alpha) = p(1, 1)\mu + p(0, 0)\beta; \\ k = 1, \dots, K_0 - 1, s = 0 \\ p(k, 0)(\lambda P_0(k) + k\mu + \beta) = \\ p(k + 1, 0)(k + 1)\mu + p(k - 1, 0)\lambda P_0(k - 1) + p(k, 1)\alpha; \\ k = 1, \dots, K_0, s = 1 \\ p(k, 1)(\lambda P_1(k) + k\mu + \alpha) = p(k + 1, 1)(k + 1)\mu + \\ p(k - 1, 1)\lambda P_1(k - 1) + p(k, 0)\beta; \\ p(K_0, 0)(K_0\mu + \beta) = \\ p(K_0 - 1, 0)\lambda P_0(K_0 - 1) + \alpha \sum_{k=K_0}^{K_1} p(K_0, 1); \\ n = K_0 + 1, \dots, K_1 - 1, s = 1 \\ p(k, 1)(\lambda P_1(k) + k\mu + \alpha) = \\ p(k - 1, 1)\lambda P_1(k - 1) + p(k + 1, 1)(k + 1)\mu; \\ p(K_1, 1)(K_1\mu + \alpha) = p(K_1 - 1, 1)\lambda P_1(K_1 - 1), \end{cases} \quad (13)$$

where $p(k, s)$, $(k, s) \in L$ is the stationary probability distribution.

IV. RECURSIVE ALGORITHM

The process representing the system states is not a reversible Markov process. Hence, we propose a recursive algorithm for calculating the stationary probability distribution $p(k, s)$, $(k, s) \in L$ for the system. We further consider the derivation of non-normalized probabilities $q(k, s)$, $(k, s) \in L$.

Lemma 1:

1. The values of non-normalized probabilities $q(k, s)$ are calculated with

$$q(0, 0) = 1,$$

$$q(0, 1) = x,$$

$$q(k, s) = \delta_{ks} + \gamma_{ks} \cdot x, (k, s) \in L : k > 0,$$

$$x = \frac{(K_1\mu + \alpha)\delta_{K_1,1} - \lambda P_1(K_1 - 1)\delta_{K_1-1,1}}{\lambda P_1(K_1 - 1)\gamma_{K_1-1,1} - (K_1\mu + \lambda)\gamma_{K_1,1}}. \quad (14)$$

2. The coefficients δ_{ks} and λ_{ks} are obtained by recursive equations as

$$\delta_{00} = 1, \quad \gamma_{00} = 0;$$

$$\delta_{01} = 0, \quad \gamma_{01} = 1;$$

$$\delta_{10} = \frac{\lambda P_0(0) + \beta}{\mu}, \quad \gamma_{10} = -\frac{\alpha}{\mu};$$

$$\delta_{11} = -\frac{\beta}{\mu}, \quad \gamma_{11} = \frac{\lambda P_1(0) + \alpha}{\mu};$$

$$k = 2, \dots, K_0$$

$$\delta_{k0} = \frac{\lambda P_0(k - 1) + (k - 1)\mu + \beta}{k\mu} \delta_{k-1,0}$$

$$- \frac{\lambda P_0(k - 2)}{k\mu} \delta_{k-2,0} - \frac{\alpha}{k\mu} \delta_{k-1,1},$$

$$\gamma_{k0} = \frac{\lambda P_0(k - 1) + (k - 1)\mu + \beta}{k\mu} \gamma_{k-1,0}$$

$$- \frac{\lambda P_0(k - 2)}{k\mu} \gamma_{k-2,0} - \frac{\alpha}{k\mu} \gamma_{k-1,1};$$

$$k = 2, \dots, K_0 + 1$$

$$\delta_{k1} = \frac{\lambda P_1(k - 1) + (k - 1)\mu + \alpha}{k\mu} \delta_{k-1,1}$$

$$- \frac{\lambda P_1(k - 2)}{k\mu} \delta_{k-2,1} - \frac{\beta}{k\mu} \delta_{k-1,0},$$

$$\gamma_{k1} = \frac{\lambda P_1(k - 1) + (k - 1)\mu + \alpha}{k\mu} \gamma_{k-1,1}$$

$$- \frac{\lambda P_1(k - 2)}{k\mu} \gamma_{k-2,1} - \frac{\beta}{k\mu} \gamma_{k-1,0};$$

$$k = K_0 + 2, \dots, K_1$$

$$\delta_{k1} = \frac{\lambda P_1(k - 1) + (k - 1)\mu + \alpha}{k\mu} \delta_{k-1,1}$$

$$- \frac{\lambda P_1(k - 2)}{k\mu} \delta_{k-2,1},$$

$$\gamma_{k1} = \frac{\lambda P_1(k - 1) + (k - 1)\mu + \alpha}{k\mu} \gamma_{k-1,1}$$

$$- \frac{\lambda P_1(k - 2)}{k\mu} \gamma_{k-2,1}. \quad (15)$$

Here, we note that the probability distribution $p(k, s)$ is produced with the following equation

$$p(k, s) = \frac{q(k, s)}{\sum_{(i,j) \in L} q(i, j)}, (k, s) \in L. \quad (16)$$

Lemma 2:

1. The performance metrics of our LSA model with one multi-tenant band and the unavailability probability B , pre-emption probability Π , and the average number of users \bar{K}

may be established as follows:

$$\begin{aligned}
 B &= \sum_{k=0}^{K_0-1} (1 - P_0(k))p(k, 0) + \sum_{k=0}^{K_1-1} (1 - P_1(k))p(k, 1); \\
 \Pi &= \sum_{k=K_0+1}^{K_1-1} \frac{\alpha}{\alpha + k\mu + \lambda P_1(k)} \frac{C_{k-1}^{k-K_0-1}}{C_k^{k-K_0}} p(k, 1) \\
 &\quad + \frac{\alpha}{\alpha K_1 \mu} \frac{C_{K_1-1}^{K_1-K_0-1}}{C_{K_1}^{K_1-K_0}} p(K_1, 1); \\
 \bar{K} &= \sum_{k=0}^{K_0} kp(k, 0) + \sum_{k=0}^{K_1} kp(k, 1). \tag{17}
 \end{aligned}$$

V. NUMERICAL RESULTS

In this section, we focus on the scenario discussed in Section II. Particularly, we target to characterize the fine-grained probabilities of the LSA system operation with our analytical methodology e.g., the rare system events that are hard to capture by utilizing the conventional simulation-based approaches [40]. Being more specific, for the envisioned Smart City requirement of 99.999% communication reliability, the number of the events to be modeled may vary from 10⁷ to 10⁹ for a point estimation, which results in prohibitive simulation times. Therefore, our analytical approach becomes a useful tool.

Below, most of the parameters related to the channel characterization were adopted from [41]. In the V2X transmit mode, vehicles generate data as: (i) 3; (ii) 5; or (iii) 10 packets/second per vehicle [42]. The number of cars per cell is estimated based on the typical urban density¹ and the cell size, as $\lambda = p_n * \Pi * R^2 * c$, where p_n is the number of packets generated by one device per time slot, c is the device density per square km based on the selected city. Here, $c = Cars/CitySquare$, where $CitySquare = 8.382$ mln km² and $Cars = 2635.9$ mln. The data rate is set to 1 Mbps per device, which is suitable for the telemetry and low-quality video streaming [42].

In this work, we assume that the LSA band unavailability is approximately once per 20 minutes. We also summarize the initial data related to our example in Table 2. We further focus on the following set of metrics of interest: (i) the average number of active users in the system K and (ii) the probability for the user to not be served Π based on the cell radius R and/or the BS transmit power P .

The dependence of the ‘service unavailable’ probability based on the cellular transmit power is offered in Fig. 6. Here, the probability in question lowers as the transmit power decreases. This behavior could be explained by the higher per-user throughput delivered when a higher transmit power is utilized. The second factor that influences this probability is as follows: when the spectrum is less accessible in general, the interruption probability is lower as well. Similar behavior

¹See “Number of licensed cars in London, England between 1995 and 2015”, 2017: (<https://www.statista.com/statistics/314980/licensed-cars-in-london-england-united-kingdom/>)

TABLE 2. Key parameter settings.

Notation	Dynamic value		
	Scenario 1	Scenario 2	Scenario 3
R	200 → 400 m	200, 400 m	200, 400 m
p_1^{max}	23 dBm (0.2 W), 42 dBm (15.58 W)	23 → 42 dBm	23 dBm (0.2 W), 42 dBm (15.58 W)
λ	10	10	2 → 10

Notation	Static value
ω	10 MHz
L	15
α^{-1}	1200, 1800 s
β^{-1}	20 s
p_0^{max}	$p_1^{max}/2$
d_0	$R/15$
r_0	1 Mbps
μ^{-1}	0.1 s
N_0	-60 dBm
G	197.43
κ	5

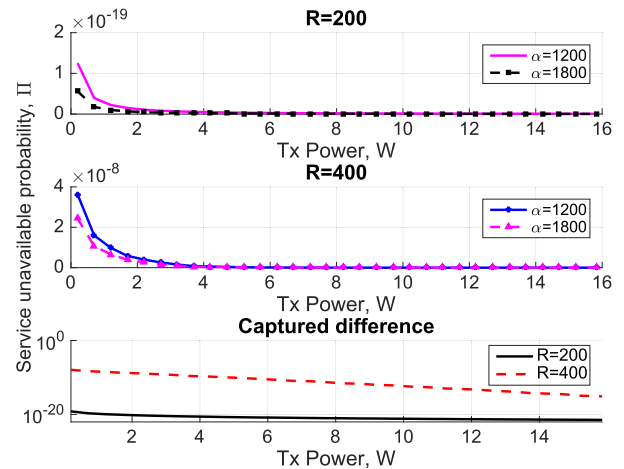


FIGURE 6. Session interruption probability as function of downlink transmit (Tx) power.

may be observed in Fig. 7, where we analyze the cell radius. Considering a fairly small cell with the radius of 200 meters, the expected average number of users generally increases. If the cell radius grows to 400 meters, the observed peak could be explained by the higher distance between the user and the BS. In other words, if the transmitter and the receiver are sufficiently far apart from each other, the offered transmit power may be insufficient to provide the guaranteed throughput.

Further, the number of served users increases with respect to the cell radius, and the corresponding results are depicted in Fig. 8. However, in case where the transmit power is higher, such an increase would be less notable. At the same time, the service unavailable probability grows proportionally to the cell size, as it is shown in Fig. 9.

The bottom plots in Figs. 6–8 report on the rare events that are possible to capture with our analytical model. Indeed, in terms of characterizing the mean number of serviced users, the obtained results indicate only marginal fluctuations. On the other hand, with respect to the service interruption probability (see Fig. 6 and 8), predicting the connectivity

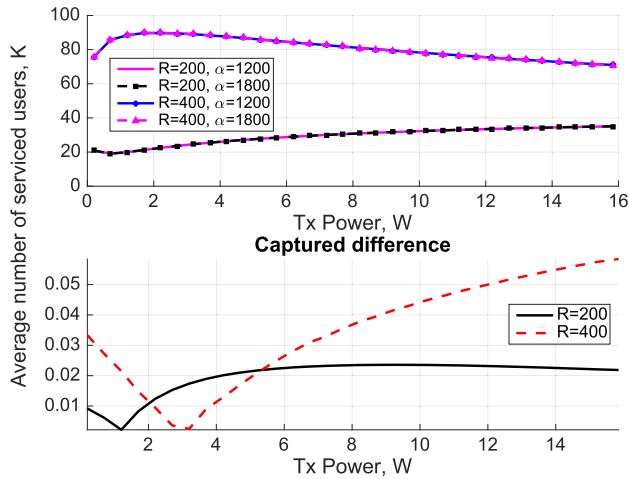


FIGURE 7. Average number of users in the system vs. downlink Tx power.

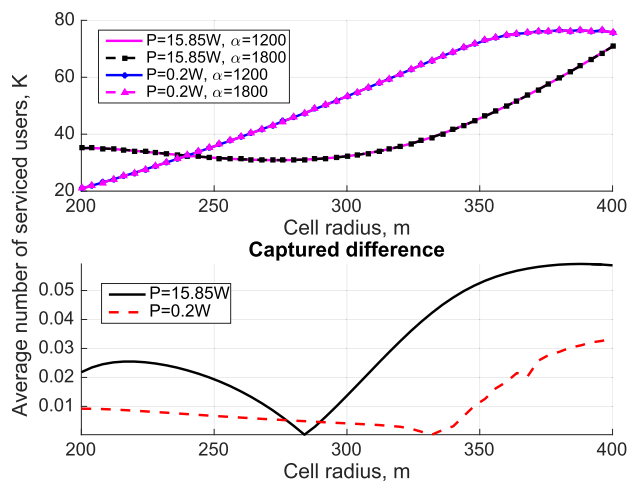


FIGURE 8. Average number of users in the system vs. cell radius.

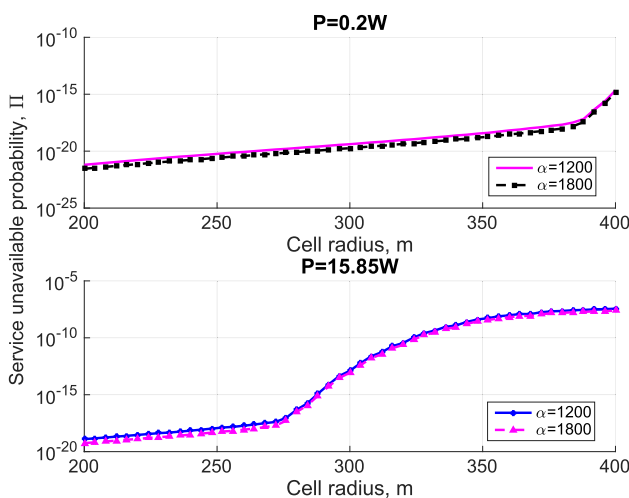


FIGURE 9. Session interruption probability vs. cell radius.

failures on the order of 10^{-20} is essential to confirm sufficient system-level reliability i.e., when targeting the levels of ‘5 nines’ (99.999) or higher.

VI. CONCLUSIONS

The emerging paradigm of the Smart City as a 5G application allows for interconnected and remotely controlled machines from a large urban-scale MTC cluster to form a highly-dense environment. In this context, one of the key enablers for dynamic radio spectrum management is becoming the LSA framework that permits more flexible control of demanding V2X services, which are addressed in this work. In this paper, we studied a characteristic urban LSA use case, where the spectrum license owner in a Smart City uses its frequency resources only occasionally, for small and localized portions. Based on the premise that the cellular network availability in a city is high, the LSA licensee (cellular network operator) has an opportunity to reuse the incumbent’s underutilized spectrum for the significant portions of time.

The analytical framework developed in this work enables to capture rare events in the considered scenario, thus providing the much needed detailed assessment, while simulation may fail to offer the desired precision. We thus studied the service unavailability probability and the average number of serviced users per cell in the urban LSA use case. We also demonstrated that while the average number of users in the LSA bands may not require high precision, the service interruption probability is of more interest for the technology operators due to its intricate fine-grained behavior.

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